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UNIVERSITY OF MARYLAND

DEPARTMENT OF PHYSICS AND ASTRONOMY

COLLEGE PARK, MARYLAND

FINAL REPORT

TO

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

ON

PROPERTIES OF LARGE NEARLY PERFECT CRYSTALS AT VERY LOW TEMPERATURES

NAG-1-151

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I. Summary

The research funded by this grant is to measure the Q of several materials at milli-Kelvin temperatures. Toward this, it was necessary to build a cryostat capable of holding a dilution refrigerator with a large enough milli-Kelvin volume to contain the crystals. This cryostat has been built and tested. Its construction is described in Section II.

The materials under study will be magnetically levitated in order to isolate them and increase the measured Q as much as possible. The levitation coils have been built and also tested. The theory and design is discussed in Section III.

Preliminary Q measurements have been carried out on 6061 aluminum alloy and on single crystal silicon. These were both measured on a four-point suspension with capacitor end plates as the transducer. The results are summarized in Table I.

Material	Temperature	Q
Silicon	300K	$6X10^6$
	77K	$4X10^7$
Aluminum	300K	$4X10^5$
	77K	$6X10^5$
	4.2K	$5X10^6$

II. MILLI-KELVIN CRYOSTAT

The study of the properties of single crystal silicon and sapphire by our group at the University of Maryland has indicated that temperatures below that of liquid helium is needed in order to more thoroughly understand the mechanisms of accoustic loss in these crystals. Toward this we have recently acquired a He^3 - He^4 dilution refrigerator from the S.H.E. Corporation. This device will allow us to reach temperatures of approximately .02 K. Because of the size of the crystals under study, however, a fairly large volume would have to be cooled. This necessitated the construction of a liquid helium cryostat of a size and configuration unavailable commercially. This section describes the design and the testing of this cryostat. Also the design of the experiment vacuum chamber and adaptor for the dilution refrigerator insert is described.

Structure

A drawing of the stainless steel portion of the cryostat appears in Figure 1. The dimensions shown allow a final .02 K volume of $\sim$35ℓ.

The outer wall of the cryostat is at room temperature and is 25" diameter X 72" long X 3/16" thick. Inside this is the liquid nitrogen shield which is a shell formed by two co-axial cylinders of 22" and 19" diameters X 68" long with thicknesses of 1/16" and 1/8" respectively. This liquid nitrogen tank has a volume of 108 ℓ. Across the bottom of this tank is a 1/16" thick copper plate for thermal shielding. Also for thermal shielding is a 1/16" thick copper liner welded to the inside of the tank and extending 48" from the top. The entire liquid nitrogen tank is suspended from three stainless steel pipes 1/4" I.D. X 3/32" wall thickness. Two of these pipes end just inside the tank and are used as vents for the

liquid nitrogen. The third pipe extends to the bottom of the tank and is used for filling. On the top of the cryostat is a flange 20" O.D. and 17.5" I.D.

Thermal considerations lead to the use of a fiberglass neck tube for the inner container where the liquid helium would be. A drawing of this vessel appears in Figure 2. It is 16" I.D. X 68" long. The bottom of the vessel is an aluminum can 32" long X 1/8" thickness with a 3/8" flat bottom plate. This is epoxied to a G-10 fiberglass tube which is 36" long X 3/16" thickness. The top of the fiberglass tube is epoxied to an aluminum flange 20" diameter which mates to the top flange of the rest of the cryostat with an o-ring gasket made of Parker O-ring compound B612-70 as shown in Figure 3. The entire cryostat is shown in Figure 4.

To the bottom of the liquid nitrogen tank was thermally attached a container holding $\sim$3 lbs. of Type 5A Linde molecular sieve material. This was to absorb any residual nitrogen left in the vacuum space after pumping. A graph of the absorbance of Type 5A is shown in Figure 5. To the bottom of the liquid helium container was attached ~1.5 lbs. of carcoal, again in order to absorb any residual gas. Figure 6 shows the modified dilution refrigerator insert. The walls of the stainless steel vacuum can are 1.16" thick and those of the copper .8K thermal shield are .005" thick. The available experimental space inside the thermal shield is an upright cylinder 16" tall X 13" diameter. This represents a volume of 35ℓ.

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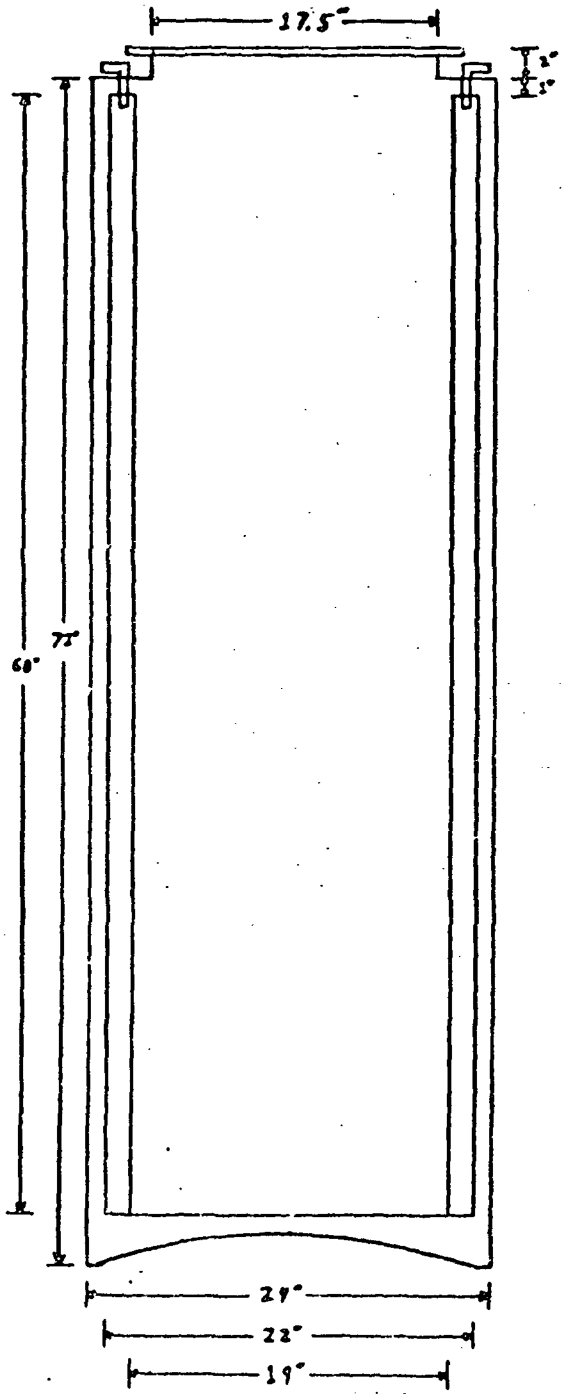

Figure 1. Stainless steel part of cryostat

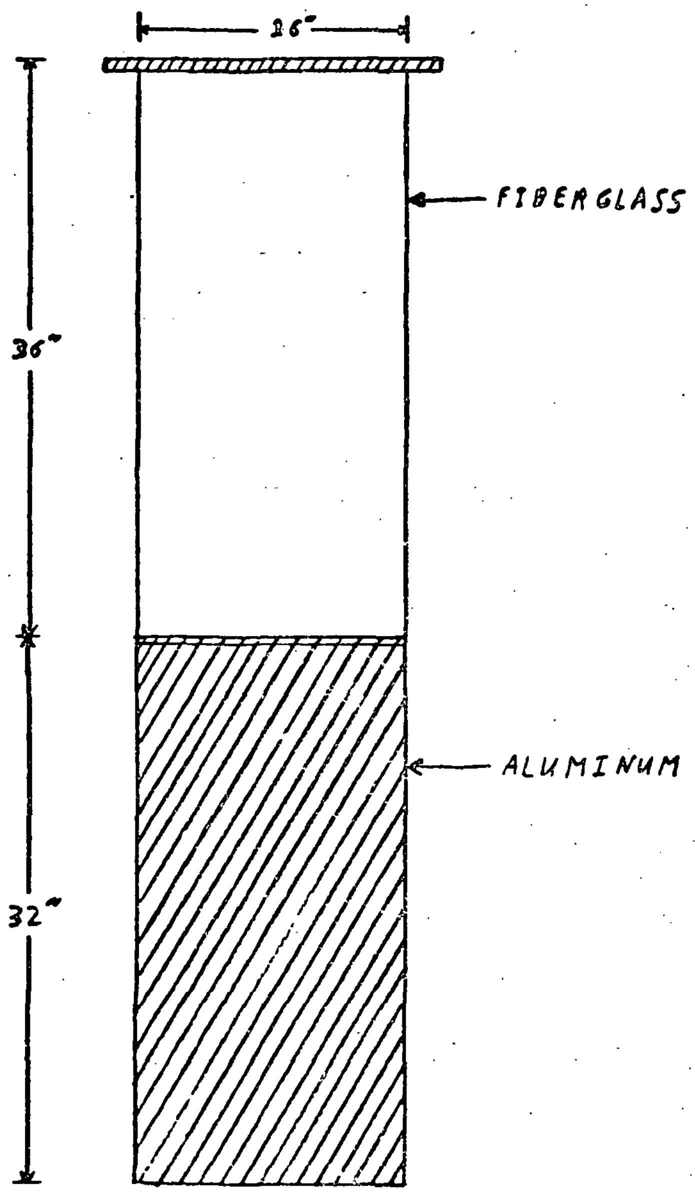

Figure 2. Fiberglass vessel

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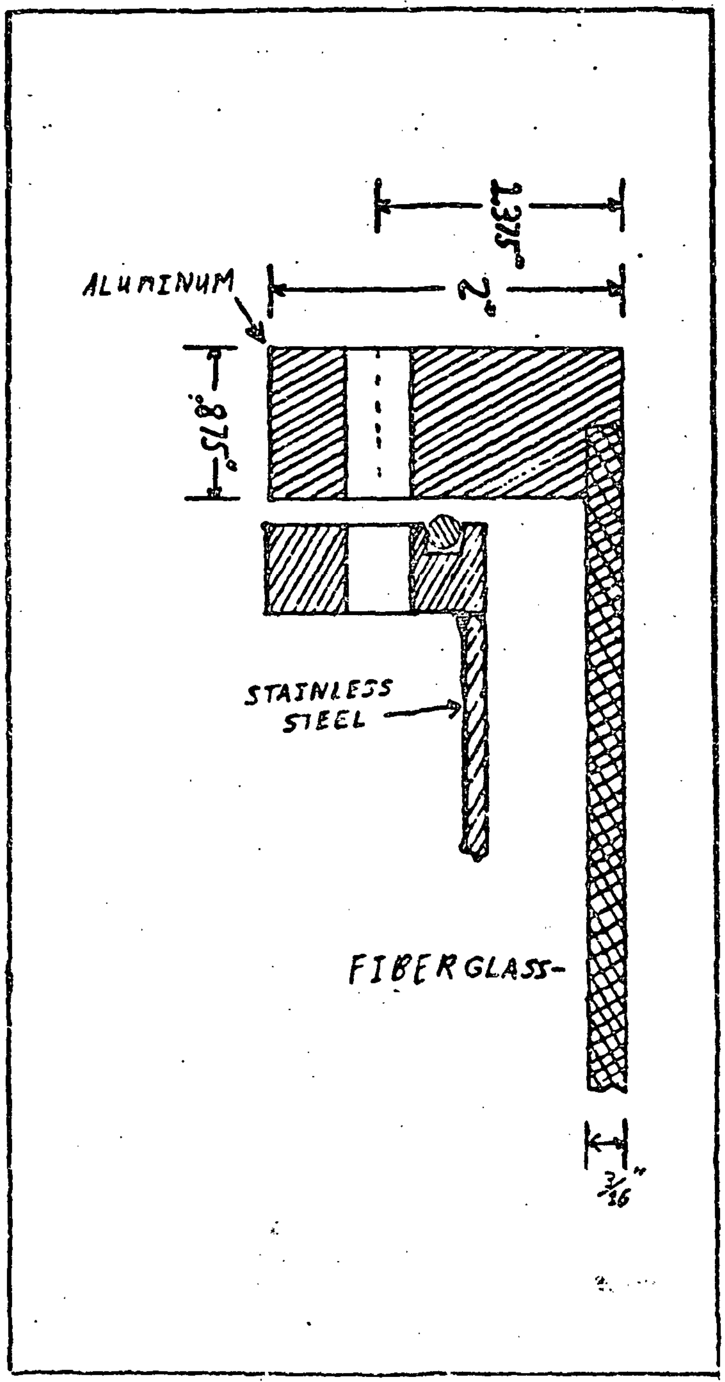

Figure 3. Stainless steel to fiberglass seal

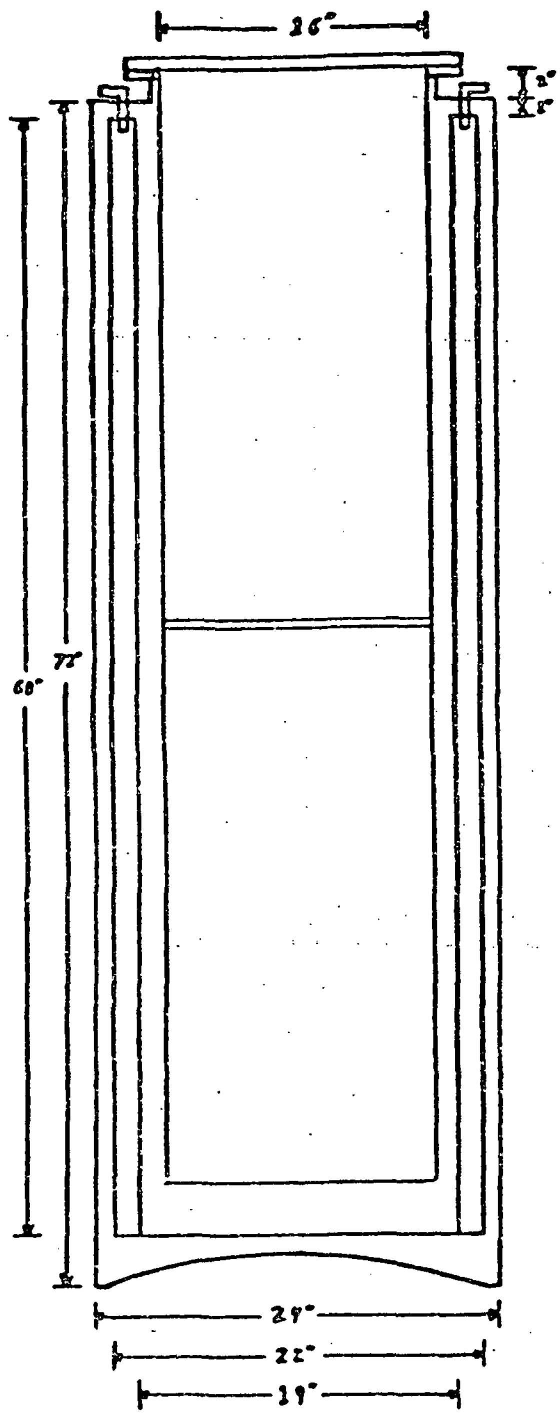

Figure 4. Complete cryostat

ISOTHERM DATA SHEET NO. 62
ADSORBATE: Nitrogen
TEMPERATURE: −196°C to −75°C

TITLE: Nitrogen Adsorption
ADSORBENT: Molecular Sieve Type 5A Pellets

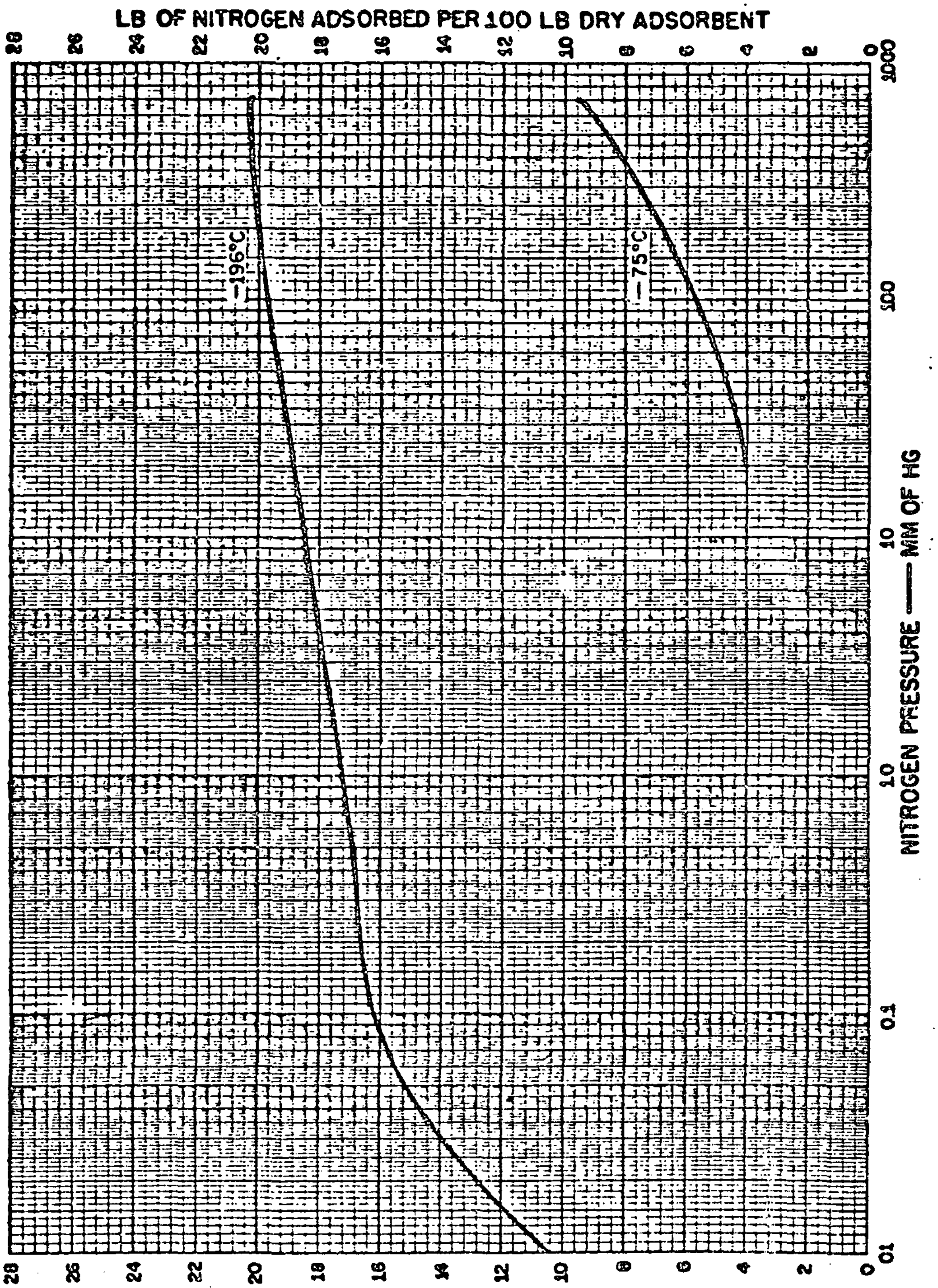

Figure 5. Linde type 5A molecular
sieve adsorbance

UNION CARBIDE ADSORBENTS & CATALYSTS

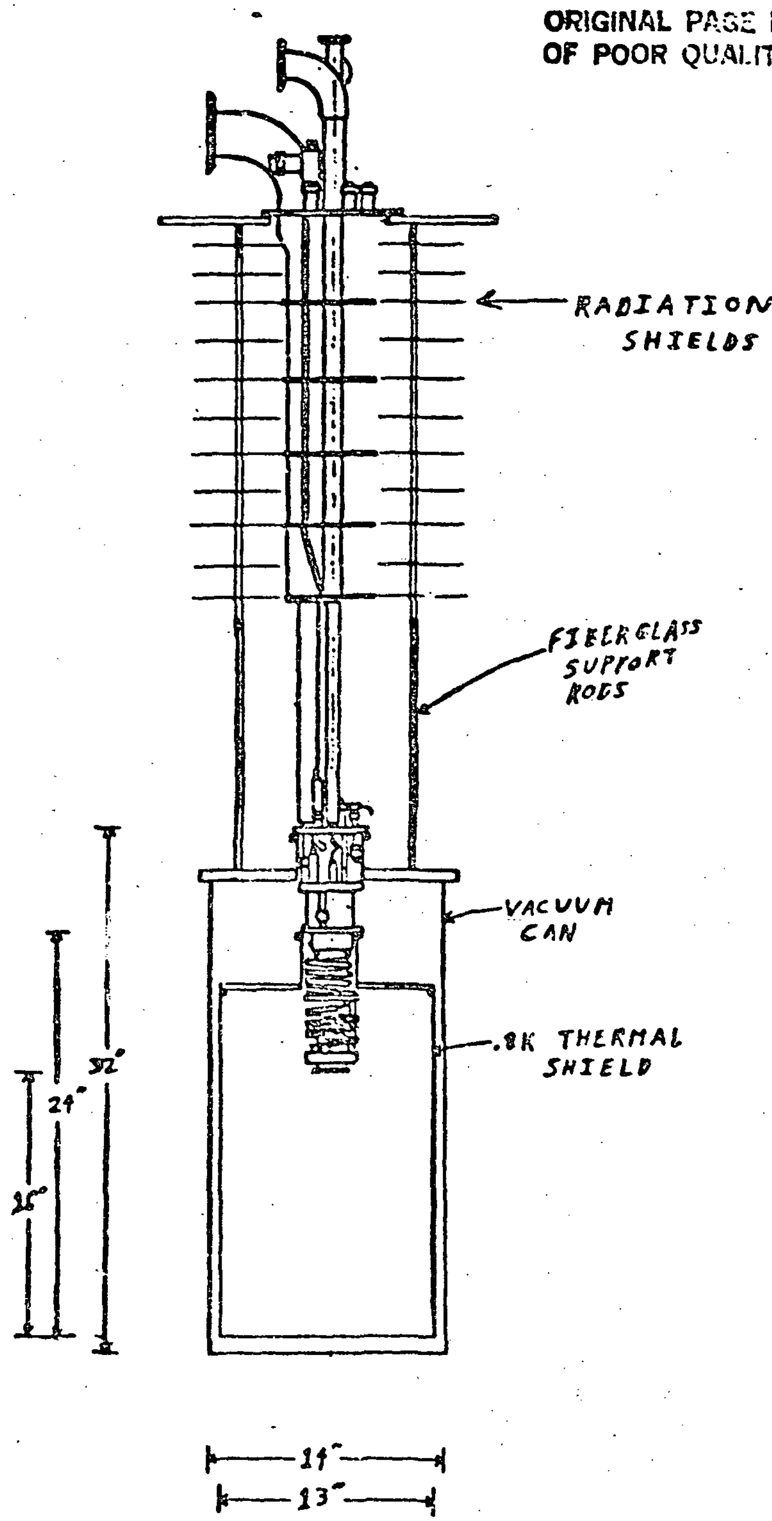

Figure 6. Dilution refrigerator insert and vacuum can

III. MAGNETIC LEVITATION

In order to isolate the crystals under investigation as much as possible they will be magnetically levitated. The crystals will be coated with niobium and suspended in a magnetic "cradle" created by superconducting coils.

The levitating coils have been designed and built as shown in Fig. 1. The bottom oval coil provides the lift and side-to-side stability. The end coils, of which only one is shown, provide the end-to-end stability and at the same time may be used as an inductive transducer. The end coils will be discussed in more detail later.

The principle of magnetic levitation is simple. A superconducting surface excludes all magnetic fields. This condition leads to solving an image problem as shown in Fig. 2. The real and the image coils repel each other since their currents are in opposite directions. This gives rise to a force between the real coil and the superconducting surface. This force may be estimated by using the expression for magnetic pressure $P = B^2/2\mu_o$. If we consider a bar 7 inches long by 2 inches diameter, the required field strength for magnetic levitation for the materials of interest is shown in Table I.

Material	$\rho\left(\frac{gm}{cm^3}\right)$	B (gauss)	I (amp)
Silicon	2.33	500	15
Sapphire	4.00	650	20
Niobium	8.58	1000	30

Table I. Required magnetic field and current for various crystals.

As can be seen, the magnetic fields required are all well below the first critical field of niobium (1600 gauss at 4 K). The London equation may, therefore, be used to find the penetration depth of the magnetic field. The London equation states that the magnetic field varies exponentially with distance into the superconductor with characteristic length λ_L called the London penetration depth. For niobium, λ_L = 390 A. Therefore, a coating of 1μm thickness would be adequate. This thickness of niobium will be sputter deposited on the silicon and sapphire crystals.

The current required to levitate the crystal can be calculated using the equation $B = \mu_o I n$, where n is the turn density of the coil. This equation is valid in the region where the distance between the coil and the super conductor is small compared to the characteristic dimensions of the coil. The results of these calculations are shown in the last column of Table I. The niobium bar has been levitated. The current that was required for levitation was 30 ± 1 amp. This agrees very well with the above estimates.

The end coil circuitry is shown schematically in Fig. 3. A persistent current is stored in the circuit by turning on the heater shown, thereby turning that portion of superconducting wire normal. The current is applied as shown and the heater turned off. A supercurrent is now stored through the primary of the signal transformer and the parallel combination of the end coils. If we let the end coil inductances equal each other and call this inductance L_0 and call the primary of the transformer L_3, we can solve for the electromagnetic energy in this circuit for a given end displacement. The mode where the bar moves as a whole will pertain to the end-to-end

stability. The energy stored for this mode is given by,

$$E = E_0 \left[1 + \frac{\alpha^2}{1+\gamma}\right], \tag{1}$$

where $E_0 = L_0 I_0^2 (1 + \gamma)$, $\gamma = 2L_3/L_0$, $\alpha = \delta/d$, I_0 is the current through each end coil, δ is the amplitude of displacement, and d is the distance between the bar and the end coil. From this equation we may find the restoring force for end-to-end displacements:

$$F_{el} = \frac{2L_0 I_0^2}{d^2}\ \delta. \tag{2}$$

In order to keep the bar level, the levitation coils were suspended from a knife edge support. Since the levitated bar is on essentially a frictionless plane, the force tending to displace the bar from a centered position is given by,

$$F_{grav} = m\ g\ \sin\Theta \approx m\ g\ \frac{\delta}{h}, \tag{3}$$

where h is the distance between the knife edge and the center of mass of the bar. As can be seen, for small angles, this acts like a negative spring. By equating these two forces we can find the minimum current necessary for stability,

$$I_{o_{min}} = (m\ g\ d^2/2\ L_0 h)^{½}. \tag{4}$$

The above problem can be repeated looking at the fundamental resonance mode of the bar. The electromagnetic energy in this case is given by,

$$E = E_0 \left[1 + \frac{\alpha}{1+\gamma} + \left(\frac{\alpha}{1+\gamma}\right)^2\right]. \tag{5}$$

The linear term above represents a constant force pushing on both ends of the bar and the second order term is the A.C. energy corresponding to the

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resonance. The portion of this A.C. energy stored in the primary of the transformer is given by,

$$E_3 = 2\, L_3\, I_o^2 \left(\frac{\alpha}{1+\gamma}\right)^2. \tag{6}$$

The bar's mechanical energy is,

$$E_{mech} = \tfrac{1}{4}\, m\, \omega_o^2 \delta^2, \tag{7}$$

where ω_o is the resonance frequency. The ratio of these two energies gives the coupling constant, β:

$$\beta = \frac{E_3}{E_{mech}} = \frac{8\, L_3\, I_o^2}{d^2 m\, \omega_o^2\, (1+\gamma)^2}. \tag{8}$$

If the above expression for minimum current (Eq. 4) is put into the equation for β, the minimum β may be found. This number is important as it determines the amount of coupling of energy out of the bar and consequentially effects the Q.

$$\beta_{min} = \frac{2\, g}{h\, \omega_o^2}\, \frac{\gamma}{(1+\gamma)^2}. \tag{9}$$

In the case of the niobium bar which was levitated, this value is $\beta_{min} = 5 \times 10^{-10}$. If we assume a Q value for the superconducting electrical circuit of 10^4, this gives an upper bound for the measured Q of a levitated bar of $Q \sim 10^{13}$.

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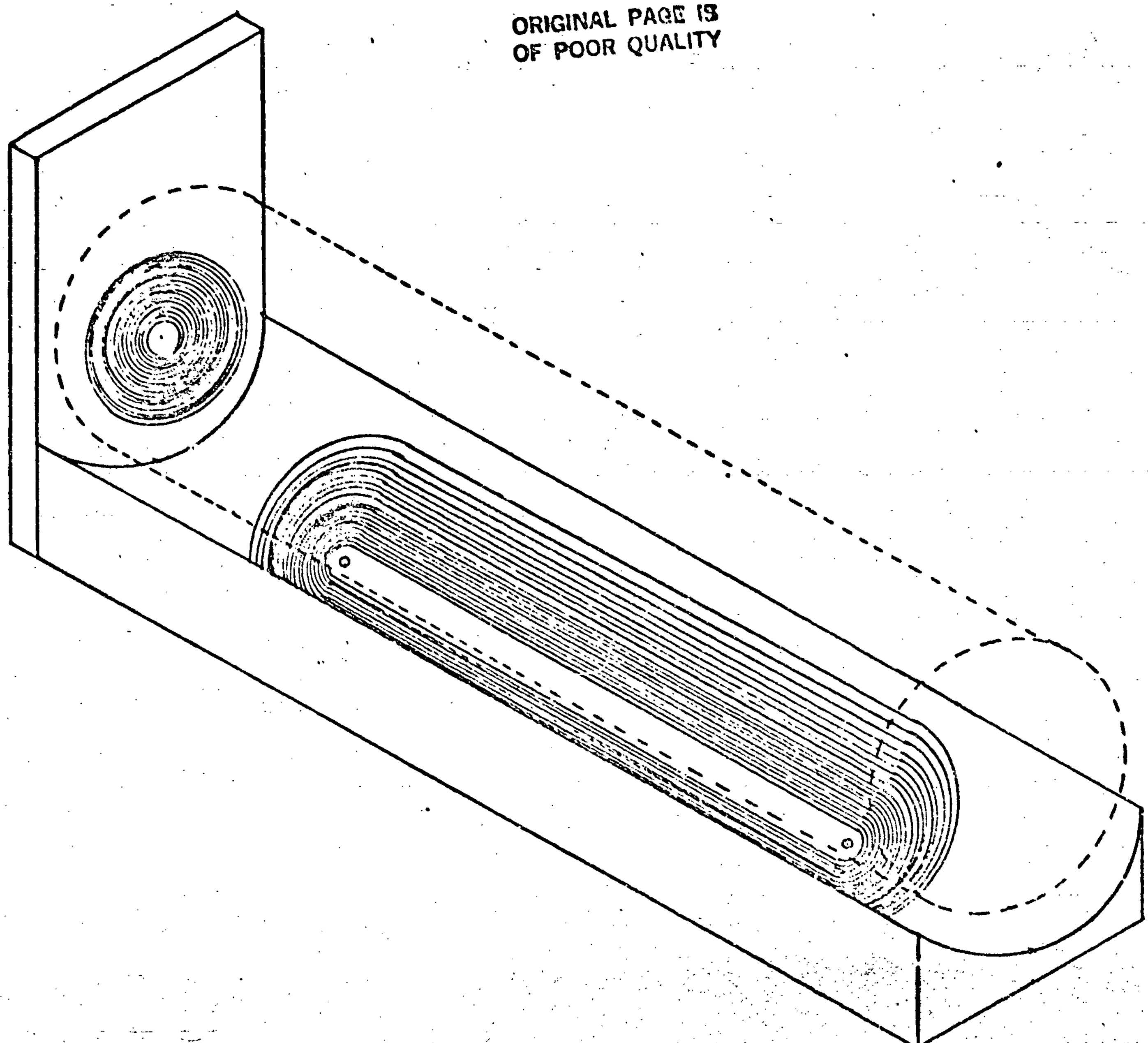

FIG. 1. MAGNETIC LEVITATION COILS

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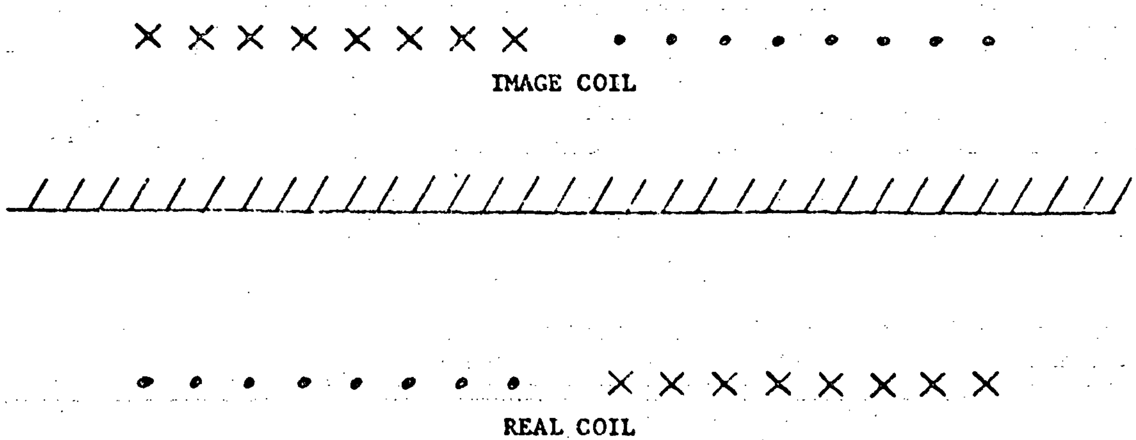

FIG. 2. IMAGE CURRENTS FROM
A SUPERCONDUCTING PLANE

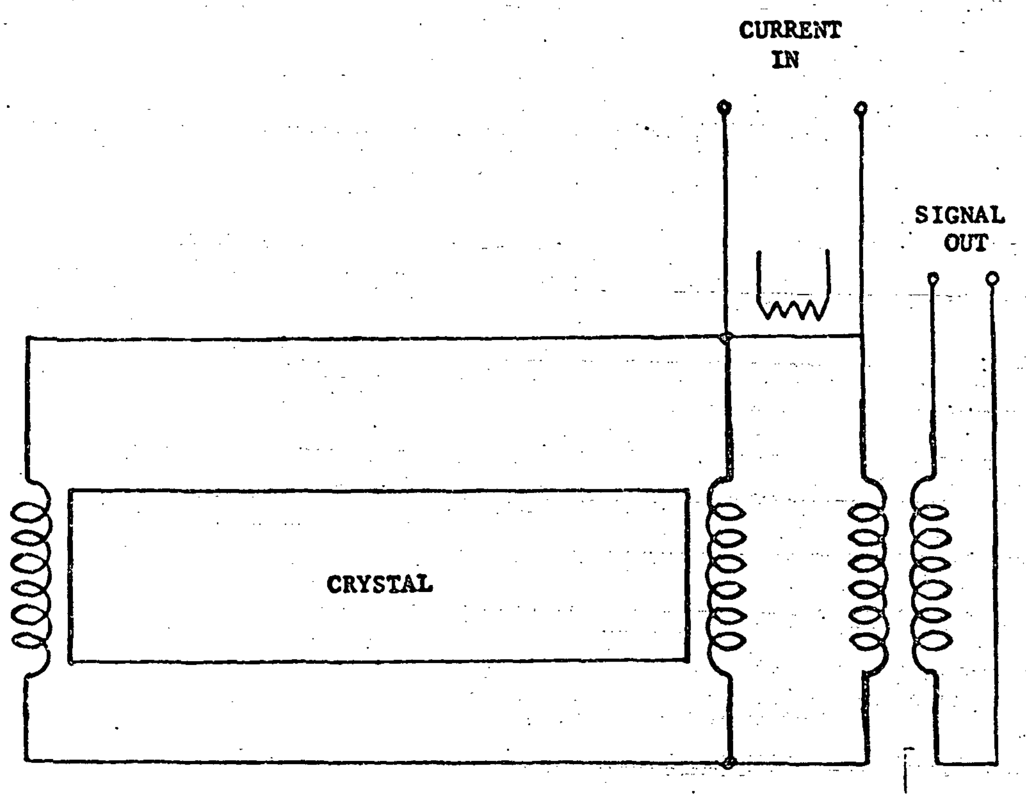

FIG. 3. SUPERCONDUCTING INDUCTIVE PICKUP